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ABSTRACT

During the JET Preliminary Tritium Experiment (PTE), an estimated 2×10^{12} Bq (1.1×10^{21} atoms) of tritium was injected into the JET vacuum vessel. A series of experiments was performed whose purpose was to deplete the torus of tritium, to compare the effectiveness of different methods of tritium removal, and to obtain a quantitative understanding of the processes involved. The effectiveness of the cleaning procedures was such that the normal tokamak programme was resumed one week after the PTE and routing of exhaust gases to atmosphere after two weeks. The release of tritium from the vessel was found to scale with the deuterium release from the vessel, suggesting that dilution and mixing of the hydrogen isotopes in the vessel walls is important. High density, disruptive tokamak discharges were found to be the most successful plasma pulses for tritium removal. Purges with deuterium gas were also effective and have the advantage of operational simplicity. Helium discharges, on the other hand, resulted in low tritium release from the vessel walls. It was demonstrated that the tritium release rate could be predicted using data from hydrogen to deuterium changeover experiments. Using the superior quality of data available from the tritium clean-up experiment, the physical mechanisms necessary to describe the hydrogenic uptake and release from the JET torus were identified. The release of tritium is reproduced using a model which incorporates implantation into a thin surface layer as well as diffusion of tritium into and out of the bulk material.

1. INTRODUCTION

JET has planned, as a main goal of its experimental programme, an extended period of operation with tritium in the years 1995/6. It has become apparent in recent years that a consistent approach to the tritium phase requires early operational experience with a limited inventory of tritium. The Preliminary Tritium Experiment [1] or PTE, performed during November 1991, was the first step in this direction. The PTE had the following aims:

i) to underpin the predictions of fusion performance during the full D-T phase;
ii) to gain operational experience with tritium handling. Particular emphasis was placed on tritium accounting, the torus inventory and its removal;
iii) to demonstrate the production of more than 1 MW of fusion power for 2 seconds.

The PTE was highly successful in all these respects [1]. This paper reports on the results of experiments subsequent to the PTE which were performed in order to

assay the tritium remaining in the first wall of the JET vacuum vessel, to study methods of tritium removal, and to arrive at an understanding of the processes involved. The results from these experiments may permit predictions of tritium inventories and their removal rates for the JET tritium phase and for other D-T fuelled tokamaks. The PTE experiment itself will only be described in so far as it is pertinent to establishing the background for this paper.

An important feature of the PTE was the use of neutral beam injection for the tritium fuelling in order to keep the tritium inventory in the torus as low as possible. Gas fuelling, although technically simple, has the drawback that 10%, at best, of the atoms fed into the torus arrive in the plasma core, with the rest staying in the vessel wall [2]. Although the overall efficiency of neutral beam fuelling, including the efficiency of the beam ion source and the beamline neutraliser, is similar to that for gas fuelling, approximately 95% of the tritium remains on the cryopanels and other components within the neutral beam system. The operation of the neutral beam system and the recovery of tritium from it is described elsewhere [3-5].

A purpose-built tritium recovery and monitoring system [3,5] was prepared for and operated during the PTE. Provision was made for independent cross-checks of all measurements used in the tritium accounting process. For example, absolutely calibrated ionisation chambers were used as the primary diagnostic for tritium concentration in the gas exhaust and these were backed up by a gas sampling system and by residual gas analysis. It is gratifying to note that not only were the different methods of tritium accounting in agreement but a remarkable overall accuracy was achieved as well [5].

The post-PTE experiment was planned and executed with the help of a multi-reservoir model for hydrogenic retention and release [6]. The small number of parameters in the model were fixed using results from experiments where the tokamak working gas was changed from deuterium to hydrogen and back again. In fact, the tritium experiment is a more accurate determinant of some of the model parameters and demonstrated the need for improvements in the modelling as discussed in Section 6.2. However, the model did predict the tritium behaviour well in the weeks after the PTE. It also demonstrated that the calibration of a realistic model for hydrogen release using hydrogen-to-deuterium changeover results would be a valuable procedure for any plasma device preparing for operation with tritium.

The paper is organised as follows. The next section will describe the PTE experiment itself and will give an estimate of the torus tritium inventory prior to

the release experiments. Following this is a functional description of the recovery and monitoring system, together with an outline of the neutron measurements used to obtain plasma tritium-to-deuterium ratios during the post-PTE period. Then the tritium release experiments are detailed, followed by sections on the results and their interpretation. A new physical model is described which includes both ion implantation into a surface layer and diffusion of tritium into the bulk material. The final section presents the conclusions of this work.

2. A DESCRIPTON OF THE PTE EXPERIMENT

In view of the planned 1992/3 shut-down to install the Pumped Divertor, the neutron induced activation of the vacuum vessel and its contamination with tritium had to be kept to acceptable levels. The full Active Gas Handling System [7] was not used. Instead a purpose-built tritium handling system, described in the next section, was deployed. These boundary conditions for the PTE constrained the total allowable on-site tritium inventory to 4.2×10^{22} atoms and the total neutron yield to 1.5×10^{18} neutrons. The tritium was delivered to JET in uranium beds which were connected to 2 out of the 16 available neutral beam sources, instead of their usual gas feed.

The plasma facing surfaces of the JET vacuum vessel consist of both beryllium and graphite components. Of the graphite components, those subject to the highest heat loads, such as the divertor target tiles, were made of carbon fibre composite (CFC) material and the rest of fine grain graphite. The material composition of the main components and the plasma configuration used in the high power phase of the PTE are shown in Fig. 1. It may be seen that most of the particle recycling and power flow in the PTE occurred on the CFC, upper X-point target tiles. Routine vacuum vessel conditioning was performed using beryllium sublimation from four sources, positioned uniformly around the torus. Typically, the thickness of the beryllium layer, averaged over the plasma-facing surfaces, was 10 nm for each sublimation. A sublimation was performed 12 hours before the two high yield PTE pulses. The next sublimation was 16 days after the PTE by which time the torus tritium inventory had been reduced by approximately a factor of ten.

A hot-ion H-mode [8] was chosen for the PTE plasma. These plasmas have the highest fusion yield of any so far obtained on JET and are compatible with the small tritium inventory. The hot ion H-mode has low target density and neutral beam fuelling only during the H-mode phase. Consequently, the hydrogenic input during the H-mode is small compared to gas fuelled discharges of the same plasma density. During termination of the high performance phase of the PTE

pulses a carbon influx (bloom) was observed [9]. Therefore, it is possible that a part of the in-vessel tritium inventory was co-deposited [10,11] with carbon.

The duration of the H-mode was maximised by running with the toroidal field direction such that the ion ∇B drift was away from the target. This has the effect of dividing the power and particle flows between the inner and outer strike zones more evenly than when the ∇B is towards the target [12]. Thus, to first order at least, no great difference should be expected in the tritium load between the inner and outer strike zones. Studies of the long-term retention of deuterium in JET [13,14] show most deuterium is retained close to the plasma contact areas, where the majority of the target material is redeposited. Assuming that the retained tritium would be similarly concentrated, an attempt was made to ensure that the heaviest tritium contamination remained at the X-point target by terminating the plasma in the X-point configuration. This procedure was not entirely successful in that the PTE discharges ended in MARFEs and as a result with poorly defined plasma-wall recycling regions.

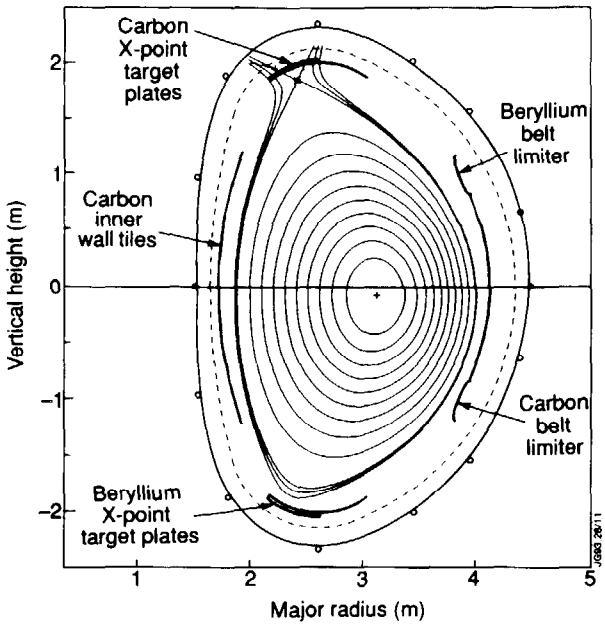

Fig. 1: The material composition of the main recycling components in the JET vacuum vessel. The plasma configuration is that used during the high performance phase of the PTE.

The two tritium fuelled neutral beam sources [4] were operated at a somewhat reduced voltage of 78 kV, so that their reliability was assured for the few pulses which would be possible with the limited tritium inventory. The neutralised beams produced a total tritium source rate of 1.5×10^{20} atoms-s^{-1}. The other 14 sources supplied a peak deuterium source rate of 1.0×10^{21} atoms-s^{-1}. Taking into account the actual beam timing employed, the tritium fuelling amounted to 13% of the total beam fuelling, which is consistent with the estimates of plasma concentrations from TRANSP analyses of the PTE [15]. It should be noted that the tritium content of the total gas release after the PTE pulses was closer to 1% because of gas fuelling before the high power phase of the discharges and desorption of previously implanted deuterium from the plasma-facing surfaces.

Prior to the two high yield PTE pulses, a series of discharges was run in which the tritium sources were fed with a mixture of 1% by volume tritium in deuterium. This series had several purposes; it allowed operational procedures for the PTE to be practised, the diagnostic systems to be checked out, and an estimate to be made of tritium transport in a deuterium plasma background. The total tritium injected into the torus in this phase of the experiment, including that lodged in the neutral beam duct scrapers, was $(3.0\pm0.6)\times10^{19}$ atoms. Although this is small compared with the $(1.10\pm0.09)\times10^{21}$ atoms injected into the two high yield pulses, useful data on outgassing and tritium recovery were obtained.

On the night of Saturday, 9th November, at the end of the PTE, the total tritium consumption from the uranium beds was $(2.08\pm0.15)\times10^{22}$ atoms or about half the available inventory. Most of the tritium was held in the neutral beam box and so priority had to be given to regeneration of the cryopanels in the beam boxes and the tritium trapped on them.

Although the torus and the neutral beam system were isolated from each other, recovery could only proceed from one of them at a time. As a result, the torus was isolated from the cryo backing pump while recovery from the neutral beam boxes was being undertaken. Consequently, there were periods of many hours where the torus pressure rose to $\sim10^{-3}$ Pa. Some of the torus exhaust was mixed with that from the beam system and this introduced a significant uncertainty in the estimate of the total tritium release from the torus before tokamak pulsing recommenced on the Monday morning.

A further complication in the estimation of the torus outgassing was the pumping of the torus through the neutral beam fast shutters. The two neutral beam boxes are each connected to the torus through two valves, a slow rotary valve and a fast shutter. The rotary valve is left open during periods of operation with neutral beam heating. The fast shutter, which is closed except during periods of beam injection, does not completely isolate the torus from the beam boxes. The quantity of tritium so collected from the torus could not be measured directly due to the much larger inventory already on the beam cryopanels. The pumping speed through the fast shutters was measured retrospectively so that the measurements of outgassing could be accurately corrected. This correction factor depends on which of the two rotary valves was open during a particular shot. During the first day of the clean-up campaign, the neutral beam box which contained the two tritium sources was not used and the correction factor is 1.32 ± 0.07. For shots when both rotary valves were open, the correction factor is 1.53 ± 0.07.

The total amount of tritium recovered from the torus over the weekend after the high-yield PTE pulses was $(3.8\pm0.6)\times10^{20}$ atoms. Therefore, including a small residual inventory from the 1% tritium injection experiments, the remaining torus inventory was $(7.3\pm1.1)\times10^{20}$ atoms. The quantity of tritium injected into the torus and the amount recovered at various times in the clean-up campaign are summarised in Table 1.

TABLE 1
TORUS TRITIUM INVENTORY
Total tritium consumption during PTE = $2.08 \pm 0.15 \times 10^{22}$ atoms

Date		Injected into torus (10^{20} atoms)	Released from torus (10^{20} atoms)	Inventory in torus (10^{20} atoms)	Inventory (measured) (10^{20} atoms)
4/11/91	1% experiments	0.30±0.06		0.30±0.06	
9/11/91	PTE	11.0±0.9	0.18±0.03	11.1±0.9	
11/11/91	Before first clean-up pulse		3.8±0.6	7.3±1.1	
25/11/91	Return to normal exhaust		5.9±0.9	1.4±1.4	$1.9^{+1.9}_{-1.0}$(a)
22/2/92	End of operations		0.5±0.2	$0.9^{+1.4}_{-0.9}$	0.34±0.17(b)

(a) Estimated from collector probe analysis (see text).
(b) From tile post mortem analysis (see text).

3. TRITIUM RECOVERY AND MONITORING SYSTEM

The JET pumping and exhaust system was modified to meet tritium recovery and monitoring requirements for the PTE. The system is shown schematically in Fig. 2 and is described in detail elsewhere [3,5]. We give a brief description so as to introduce the tritium measurements which are reported and discussed below. The main change to the forevacuum line was to replace the backing pumps with a gas collection system (GCS) using a cryopump which could then be regenerated into a closed gas storage system based on uranium beds. This purpose-built GCS was used in the clean-up of both the JET torus and the neutral beam injection boxes. Batches of gas from the two systems were processed separately to enable independent accounting for the torus and the beamlines. During periods of plasma operation the sampling manifold was connected to the torus through

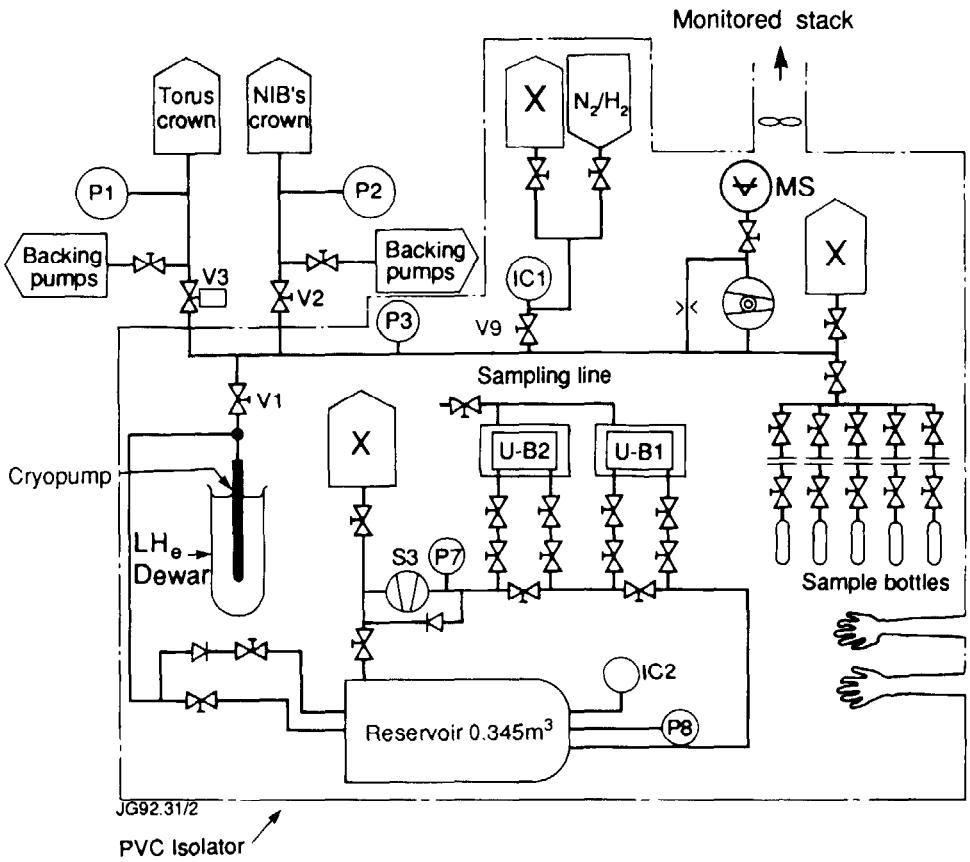

Fig. 2: The gas collection system (GCS) used for the recovery of tritium from the JET vacuum vessel and from the neutral beam boxes.

valve V3. After a discharge the cryopump was isolated from the sampling manifold (valve V1 closed) and the gas pumped from the torus was collected into the sampling manifold. Here the amount of gas collected was measured with pressure gauge P3, and the tritium content measured with calibrated ionisation gauge IC1. In addition, for certain discharges, samples were collected into bottles for separate, remote tritium counting. The normal collection time after a plasma pulse was 10 minutes, although for some discharges the torus exhaust was held for up to 40 minutes in order to measure the longer term time evolution of the vessel outgassing. After the appropriate measurements, the valve V1 was opened and the collected gas was pumped onto the cryopump and the system readied for the next JET pulse. After several discharges the cryopump was heated and the exhaust gas transferred into the reservoir shown in Fig. 2. The total tritium collected during the series of discharges was then measured using ionisation chamber IC2. The gases were then loaded into the uranium beds.

The tritium content of the plasma and of the gases exhausted from the torus after a discharge was measured using several different techniques. The sensitivity and uncertainties of the various measurements are summarised in Table 2.

TABLE 2
TRITIUM MEASUREMENT SENSITIVITIES AND UNCERTAINTIES

Measurement	Uncertainty	Sensitivity Limit (T/D)	Sensitivity Limit (T atoms)
Ionisation Chambers:			
IC1	20%	$1x10^{-5}$	$2x10^{17}$
IC2	10%	-	$1\text{-}5x10^{17}$
Quadrupole Mass Analyser	30%	$1.5x10^{-5}$	$3x10^{17}$
Sample Bottles:			
10 ml bottle	8%	-	10^9
1000 ml bottle	<0.5%	-	10^9
Neutron Yield Ratios	10%	$2x10^{-5}$	

3.1. Ionisation chambers

The main diagnostics for tritium monitoring during the PTE were the ionisation chambers shown in Fig. 2. These detectors can be operated at low pressure in ion collector mode or at high pressure in normal ionisation chamber mode [16]. An identical detector was absolutely calibrated at high pressure in ionisation chamber mode at the Los Alamos National Laboratories. This calibration was later verified by independent scintillation counting of gas samples [5]. Since IC1 was normally operated at less than 10 Pa and hence in ion collector mode, its calibration had to be derived from the calibration at higher pressure ranges. After several discharges the gauge was isolated from the sampling manifold and backfilled with nitrogen to the benchmark calibration pressure of $7.5x10^4$ Pa. The tritium concentration measured in this calibrated ionisation chamber mode was then used to calibrate the ion collector measurement. With this method the sensitivity of IC1 was found to within a statistical uncertainty of ±20%. The IC1 measurements have a sensitivity limit of ~$2x10^{17}$ atoms. IC2, which was used to measure the amount of tritium released when regenerating the cryopump, was operated in the range of pressures from $5x10^2$ Pa to $5x10^3$ Pa. This is the intermediate pressure range between the two modes of detector operation and the regime where the detector sensitivity is a function of both total pressure and the composition of the gas collected. It is known [17] that the fraction of hydrocarbons in the outgassing after a JET pulse varies with the type of plasma operation. This can create problems in

accounting due to the increased sensitivity of IC2 to tritium in hydrocarbons as compared to hydrogen. However, the gas collected in the uranium beds was sampled and found to have low hydrocarbon content (<0.04%). Again, *in situ* calibrations were performed, using a cross calibration with IC1 followed by backfilling with nitrogen as described above. With this method the sensitivity of IC2 is estimated to be known to approximately ±10%, excluding any effects due to gas composition variations.

3.2. Gas sample bottles

In addition to the real time measurements provided by IC1, the tritium content in the exhaust gas from JET was measured after-the-fact using collected samples [18]. These samples were oxidised, mixed with a scintillant, and the tritium counted using a scintillation counter. The absolute accuracy of the measurement is ±8%. Due to the limited number of available sample bottles (5 at any one time) samples were collected only after selected events, the data therefore being more sparse than that provided by IC1. On the other hand, this scintillation technique is the highest sensitivity measurement of tritium released from the torus (10^9 atoms), being able to measure tritium levels from D-D burnup in deuterium operation campaigns (~10^{16} atoms).

3.3. Quadrupole mass analyser

As well as the diagnostics shown in Fig. 2, the tritium content in the outgassing from JET was measured using a mass spectrometer located in the pumping duct. By monitoring mass numbers 2, 3, 4, and 5 and knowing the cracking patterns for operation in hydrogen and deuterium without tritium, it is possible to deduce the fraction of tritium being pumped by the increase in the mass 5 signal relative to the expected HDD background. The measurement is limited by this background to values of $T/D>5\times10^{-5}$ and is thought to have an uncertainty of ±30% or $\pm3\times10^{17}$ atoms, whichever is greater.

3.4. Neutron yield ratios

Measurements of tritium content in the gas pumped from the JET vacuum chamber can be compared with the ratio of tritium to deuterium in the plasma, measured using neutron yields. When a short pulse of neutral beam heating is applied to the plasma the neutron yield is dominated by beam-plasma reactions. In this case, since the relative collision velocity is essentially the beam speed, the measurement is not sensitive to the plasma ion temperature. Using the ratio of the D-T to D-D fusion cross sections at the beam energy, the ratio of T to D in the

plasma can be deduced from the ratio of the 14 MeV (D-T) to 2.5 MeV (D-D) neutron yields. The level of 14 MeV neutron emission is measured separately from the total neutron yield using a threshold reaction in silicon [19]. This measurement is limited at low tritium concentrations by the level of tritium produced by D-D reactions ($T/D>2x10^{-5}$).

4. DESCRIPTION OF THE CLEAN-UP SEQUENCE

Following the tritium injection experiments of Saturday, the torus clean-up campaign began on Monday morning. In order to access the same parts of the vacuum vessel as the PTE discharges, a standard clean-up discharge with similar magnetic geometry was employed. However, this discharge was different from the PTE discharges in that it included sweeping of the plasma-surface strike position so as to produce strong recycling on regions of the X-point targets which may have been areas of tritium/carbon co-deposition. The standard clean-up pulses were low power, essentially only ohmic heating, with the exception of two short neutral beam pulses which were used for neutron yield T/D measurements in the initial limiter phase of the discharge and the subsequent X-point phase.

In addition to this standard clean-up discharge, a diagnostic 'bounce-around' discharge was used to monitor the level of tritium contamination on different surfaces. In these shots, the X-point targets were avoided and the plasma was moved successively from the upper belt limiter to the inner wall and then to the lower belt limiter.

The clean-up campaign began with a series of 14 standard pulses with deuterium as the working gas, interrupted only by one 'bounce-around' discharge. Following this test of tritium release in reproducible conditions a series of variations on the standard pulse was performed. They were, in order:

i) operation of the standard pulse, but with helium as the working gas;
ii) operation in deuterium, but with increased input power (up to 14 MW);
iii) termination of the discharge with a planned high density limit disruption.

Several times during the first week of the clean-up campaign, in order to test the rate of surface isotope exchange, the torus was filled with ~2 Pa of deuterium and let 'soak' for 1-4 hours before resuming pumping.

About two weeks after the PTE the release of tritium from the vacuum vessel was low enough that the torus exhaust could be rerouted to atmosphere. At this point the efficacy for tritium removal of glow discharge cleaning (GDC) was

tested. GDC could not be performed earlier in the clean-up campaign because of the required gas load which would have been too high for the recovery system.

5. RESULTS

Using the diagnostics described in Section 3, it was possible to track the amount of tritium released from the JET vacuum vessel as a function of the shot number, integrated over a time window after the shot, and as a function of real time between shots. The dynamic range of these measurements is very large (over 5 orders of magnitude) allowing measurements of isotope exchange behaviour in a tokamak of unprecedented quality to be made. The various measurements of the quantity of tritium in the gas collection system have been found to be in good agreement (Fig. 3). There is a systematic difference between the RGA measurements and the IC1 and sample bottle data. This difference is thought to be due to an error in the calibration factor used in converting the RGA mass signals to particle numbers.

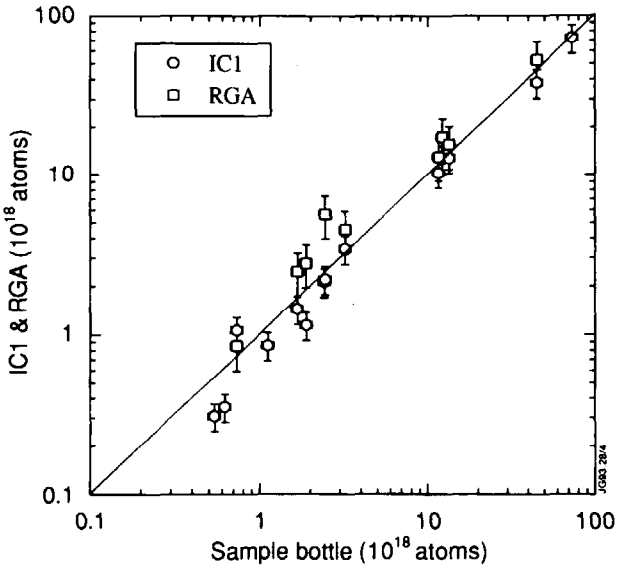

Fig. 3: Comparison of the three measurements of tritium activity in the gas collected from the JET vacuum vessel. Data from an ionisation chamber (IC1) and from a residual gas analyser are plotted relative to scintillation measurements of gas samples taken of the torus exhaust.

5.1. Tritium release as a function of discharge number

The number of tritium atoms released from the vacuum vessel is shown as a function of shot number in Fig. 4 for three different shot ranges. All of the data is for the quantity of tritium released in the first 560 s after the shot except for the solid points in Fig. 4(c), which are for an integration time of 1160 s and are included so as to present a more complete picture of the release behaviour after many discharges. For comparison, the two exponential behaviour which one gets from a multi-reservoir model of the recycling is shown with dotted lines. The solid curves in Fig. 4 are the result of our more detailed model, which is presented in Section 6.

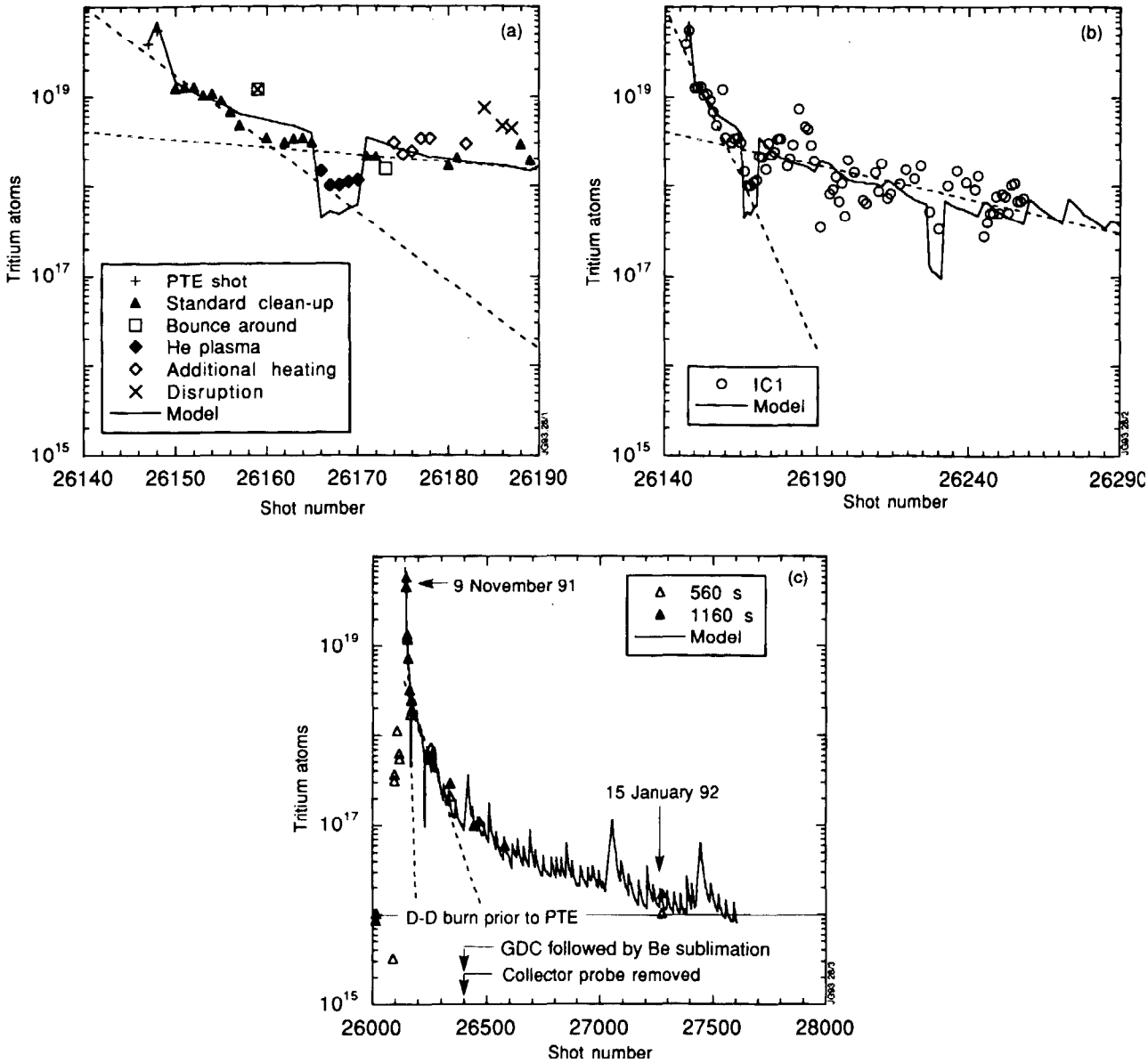

Fig. 4: The number of tritium atoms released from the JET vacuum vessel as a function of shot number. The two PTE shots were pulse numbers 26147 and 26148. All of the data are integrated over the first 560 s of outgassing after the shot, except for the solid triangles in (c) which are 1160 s integrations. The data in (a) are from the first two days of dedicated clean-up operation and are ionisation chamber measurements sorted by discharge type. The data in (b) are IC1 measurements for the first week after the PTE shots. The data in (c) are gas sample measurements covering the rest of the experimental campaign. The solid curve is the prediction of the model described in the text. The dashed lines are the results of a simple two reservoir model for the wall.

The data in Fig. 4 show that the tritium release from the torus does not follow a simple exponential behaviour, as would be predicted by a model which treated the vessel as a single point reservoir of hydrogen. In fact, the release data from the first two weeks of the clean-up campaign (Fig. 4(b)) suggest a double exponential dependence, as was observed in H/D exchange experiments in JET [6]. Similar deviations from a single exponential dependence have been reported

for H/D changeover experiments in DITE [20], TFR [21] and TFTR [22]. The two decay constants in the present data are roughly 7 pulses and 60 pulses, with the change from one slope to the other occurring after approximately 10 shots. It can be seen from Fig. 4(c) that the second exponential does not fit the tritium release after many discharges. By January 15, the tritium release level is seen to have been reduced to close to the value for tritium produced from D-D burnup alone.

The amount of tritium collected from the vacuum vessel is shown in Fig. 4(a) for the clean-up experiments performed in the first two days of operation after the PTE. The data are subdivided according to discharge type as described in the Section 4.

The helium discharges resulted in a factor of 2.5 less tritium being removed from the torus compared to the deuterium fuelled discharges. These discharges, although fuelled with helium for the most part, were initiated by breakdown of a deuterium prefill. This is done to ensure good, reproducible breakdowns and nonetheless results in plasmas with high helium content. In fact, for these shots, there was still some D in the plasma, the D_α light having decreased by a factor of 5 from its level in the standard deuterium clean-up shots. The deuterium collected from these helium shots was about 3 times lower than in the standard pulses and the tritium-to-deuterium ratio in the collected gas actually increased slightly. It is therefore probable that the tritium release in these helium shots is still dominated by deuterium-tritium exchange processes.

Applying additional heating to the standard ohmic shot produced an increase of 25-50% in the tritium release from the vessel walls. There was no strong correlation of the tritium release with input power in these shots.

Discharges which were terminated in density limit disruptions produced the most tritium collection. Twice as much tritium was released from the torus in the 10 minute collection period. In addition to the high tritium outgassing, increased amounts of deuterium were collected so that the fraction of tritium in the collected gas remained the same as was seen in the adjacent standard clean-up pulses.

The total amount of tritium collected after the two 'bounce-around' shots is confused by the first having terminated in an unintended disruption. It appears, considering the increased tritium outgassing after disruptions, that the bounce-around discharges had a tritium release equivalent to the standard pulses despite their never having touched the X-point targets which were in use during the tritium fuelling phase of the PTE. Indeed, neutron measurements of the tritium

fraction in the plasma show that this fraction is independent of the recycling surface (see Fig. 5). Furthermore, the plasma isotopic concentration is found to be the same, within experimental error, as the isotope composition in the gas collected in the GCS. *As early as the limiter phase of the second PTE shot it was clear that surfaces other than the upper target were significantly contaminated.*

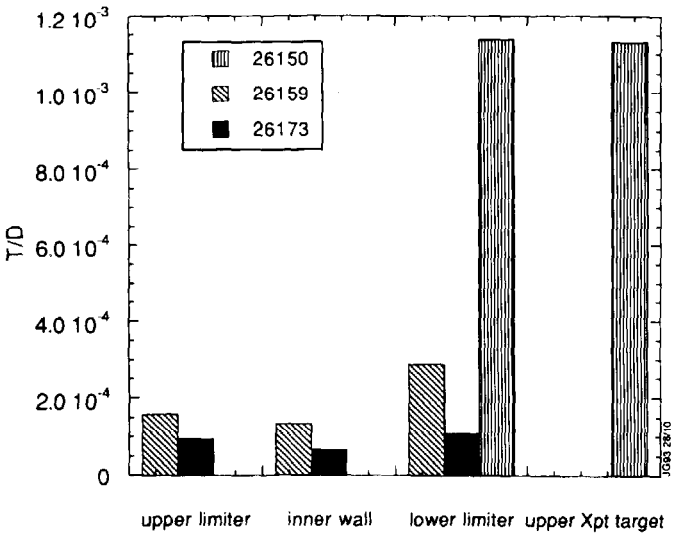

Fig. 5: T/D ratio in the plasma as a function of plasma contact surface. For shot numbers 26159 and 26173 the plasma started on the upper belt limiter, moved to the inner wall, and then to the lower belt limiter, spending ~8 s on each surface. Pulse number 26150 (the first clean-up shot) started on the lower belt limiter and then moved on the upper target plates.

Early in the clean-up campaign, it was found that tritium could be removed from the torus simply by filling it with ~2 Pa of deuterium and leaving it there, without pumping, for several hours. The amount of tritium collected in this manner exceeded that collected from the immediately preceding plasma discharges. This is, by itself, somewhat misleading as the ratio of tritium to deuterium collected when the vessel was pumped out was very close to that found in the plasma pulses (Fig. 6). The amount of tritium removed by these deuterium soaks was found to be independent of the soak time, suggesting that the vessel wall and the gas load reach equilibrium. However, it should be noted that the equilibration time was not determined and that the minimum soak duration was one hour.

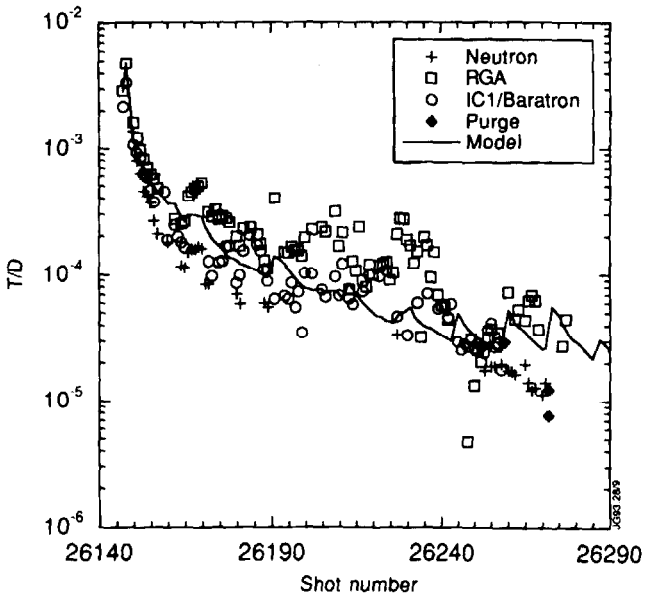

Fig. 6: T/D ratio in the plasma (the neutron measurements) and the exhaust gas as a function of shot number. Also shown are the T/D ratios in the exhaust gas of the torus after the D_2 soaks. The solid curve is the result of the model described in the text.

Glow discharge cleaning (GDC) was performed as soon as the tritium release from the vessel had been

sufficiently reduced to be compatible with the normal atmospheric exhaust system. A 20 minute glow in deuterium was found to release about 4 times the amount of tritium as a standard plasma discharge. However, the amount of deuterium consumed was equivalent to about 100 discharges, so that the T/D ratio in the exhaust was quite small. Since the gas collection system used in these experiments has limited gas handling capacity, GDC is not an attractive option for removing tritium. GDC in helium was found to be ineffective in removing tritium. In fact, the tritium release rate during helium glows was found to be less than the background outgassing rate. Immediately after the glow discharge tests, the first beryllium sublimation coating of the vacuum vessel was performed. The long term tritium recovery, shown in Fig. 4(c), shows that this had little effect on tritium release from the vessel walls.

At the same time as the change back to atmospheric exhaust a collector probe was removed from the vessel for analysis [23]. This probe was designed to have different surfaces representative of plasma-facing and shielded surfaces in the vessel. The probe was manufactured from inconel and graphite so that samples of both could be analysed for tritium content. Using four different samples from the probe and assuming that these samples were representative, i.e. that the tritium was uniformly spread throughout the torus by this time, the vessel inventory was calculated to be $1.9^{+1.9}_{-1.0}\times10^{20}$ atoms. This value is consistent with that estimated from the tritium accounting of $1.4\pm1.4\times10^{20}$ atoms (see Table 1).

About two and a half months after the PTE the torus was vented for the first time since the introduction of tritium. This was caused by a bellows failure and resulted in air leaking into an initially 300°C vessel. The air in the vessel contained about 4×10^{18} tritium atoms and therefore could be pumped out of the vessel and released to the atmosphere. Note, however, that this represents approximately 10% of the in-vessel tritium inventory at this time, which is consistent with previous work on D and T releases from JET on venting [24]: a venting closer to the time of the PTE would result in appropriately larger T levels being released from the vessel walls.

Analysis of tiles removed from the vessel at the start of the shutdown show that the tritium was uniformly spread through the vessel, with the exception of tiles subject to direct shine-through from the tritium beams [25]. The total tritium inventory was estimated from these tile samples to be $(3.4\pm1.7)\times10^{19}$ atoms. This is consistent with the final calculation of vessel tritium inventory from the measurements of tritium release ($9^{+14}_{-9}\times10^{19}$ atoms, see Table 1).

5.2. Tritium release as a function of time after a discharge

In addition to the measurement of tritium release from the torus as a function of shot number, the ionisation chamber and sample bottles in the sampling manifold were used to study the temporal behaviour of tritium release [18]. Fig. 7 shows the integrated tritium release from the torus following the two high yield tritium pulses. The release of tritium is very gradual, the time scale for release being much longer than the vacuum time constant of the torus (~20 s). The deuterium outgassing behaves in a similar manner.

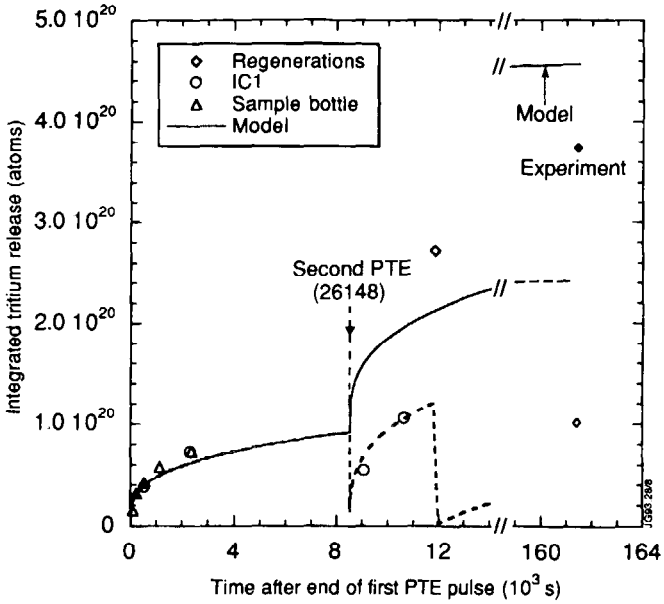

Fig. 7: Integrated tritium release from the vacuum vessel as a function time after the first PTE discharge. The solid curve is the model calculation. The dashed curve is the modelled release, zeroed after the second PTE shot in order to compare with IC1 measurements, and after the cryopump regeneration at approximately 12000 s for comparison with the measurement of integrated release over the weekend after the PTE.

Previous outgassing studies [26] have shown that the deuterium release rate, Φ_W, from the JET vacuum vessel follows a power law as a function of time:

$$\Phi_W \propto t^{-n} \qquad \text{where } 0.5<n<0.8 \qquad (5.2.1)$$

Care must be taken to distinguish between the rate of tritium release from the vacuum vessel walls, which is the quantity of interest, and the rate of tritium collection in the GCS, which is the quantity actually measured. The tritium particle balance equation can be written as follows:

$$\Phi_W = V\frac{dP_T}{dt} + (S_{NBI} + S_{TP})P_T \qquad (5.2.2)$$

where P_T is the torus pressure, V the torus volume, and S_{NBI} and S_{TP} are the pumping speeds of the vessel through the neutral beam boxes and the torus turbomolecular pumps, respectively. In our experiments, two effects make the two rates different, at different times after the shot. Firstly, the rate of rise of the

pressure in the torus (the first term on the right hand side of Eq. 5.2.2) is important immediately after the pulse. Secondly, if the gas from the torus is allowed to collect in the GCS for a long period of time, the backing pressure of the turbo pumps builds up to a sufficient level so that back streaming of gas from the GCS into the torus becomes significant. This effectively makes the pumping speed, S_{TP}, time dependent and leads to different time dependences in the vessel outgassing rate, Φ_W, and the gas collection rate, $S_{TP} P_T$. The temporal evolution of the deuterium release rate is shown in Fig. 8 for two shots in ranges of time where the two corrections described above are insignificant. The data follows the power law dependence with an exponent of 0.8.

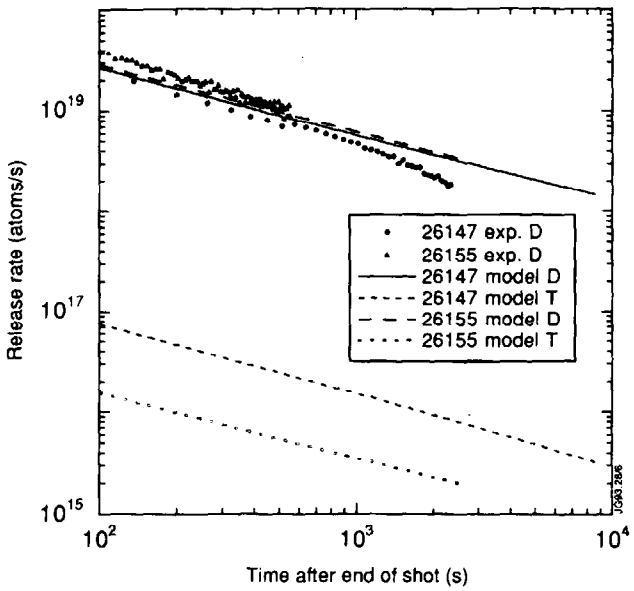

Fig. 8: The model predictions of the outgassing rate of deuterium and tritium as a function of time after the end of discharges 26147 and 26155. Experimental data for deuterium are from the GCS pressure measurements.

5.3. Summary

The results of the tritium clean-up campaign, which must be explained by any model, are summarised as follows:

i) the quantitative release versus shot number as shown in Fig. 4.;
ii) the equivalence between the tritium fraction in the plasma and that in the outgassing after the discharge;
iii) the independence of tritium concentration in the plasma on the location of the main recycling surface;
iv) the temporal variation of the outgassing of tritium after a shot;
v) the strong correlation between the tritium release after a shot and the deuterium output from that shot.

6. INTERPRETATION

6.1. Mechanisms of tritium dispersion

In the tritium discharges an attempt was made to keep the plasma in the X-point configuration both during and after the tritium injection up till the end of the discharges. The objective was to keep the tritium localised to the divertor target plates and to prevent contamination of other surfaces in the torus. It was clear from the first clean-up shot that the procedure had not been successful. In the second PTE discharge, ~2 hours after the first discharge, tritium was detected in the first, limiter phase of the shot, before the X-point was formed and thus before the plasma had directly interacted with the target plates. It was observed in later clean-up discharges that the tritium content of the plasma was the same whether the plasma was on the inner wall or the upper or lower toroidal limiters (Fig. 5). Operationally, the attempt to keep the tritium contamination localised was not optimum: in the current ramp down phase of the high yield discharges the plasma moved to surfaces other than the upper target. However, the degree to which the contamination was uniform cannot be explained by this alone.

There are at least two possible explanations for the apparent uniformity. Firstly, tritium contamination might be restricted to the X-point tiles during the discharge, with cross contamination occurring during the interpulse period via the desorption and readsorption of molecules. Secondly, the charge exchange neutrals may distribute the tritium over the walls during the discharge. These two explanations will be considered in turn.

When tritium is desorbed from a contaminated surface after a discharge, it will leave primarily in the form of DT molecules. The average number of collisions with surfaces which a DT molecule undergoes before being pumped out of the torus, N_{col}, can be estimated by comparing the collision rate with the vacuum time constant. The average particle undergoes ~10^4 collisions before being pumped out of the torus. For the tritium inventory in the vessel to redistribute itself over different surfaces requires that the desorbed tritium be reabsorbed before it can escape from the vessel. It follows that for tritium to contaminate other surfaces it must have a sticking coefficient, $\alpha > 10^{-4}$. Although the values for the sticking coefficient of molecules on graphite [27] and beryllium [28] suggest very low values at 300°C, $<10^{-8}$, values for clean metal surfaces [29] can be as high as unity.

If we assume that contamination occurs by isotopic exchange at the surface, without net sorption of molecules, then a change in the isotopic mixture of the

gas removed from the vessel gives an indication of the level of contamination of the surfaces by the gas. A measure of the rate of isotopic exchange by molecular collisions is available from the analysis of test puffs of gas injected into the torus before a day's plasma operation. The quantity of gas injected in these 'dry runs' is typically 10^{21} molecules, i.e. ≤1 monolayer over 200 m^2. The collected exhaust is equal to the quantity injected to within the uncertainty of the measurements, supporting the hypothesis of no net sorption of molecules.

The particle exhaust after a deuterium dry run before the first clean-up pulse yielded an isotopic ratio, T/D = 10^{-4}. Since this is about 10 times smaller than the T/D ratio reached during the plasma pulses which followed, the dry run T/D ratio implies a sticking coefficient $\alpha \sim 10^{-5}$. A similar analysis of a dry run with H_2 just before a changeover from deuterium to hydrogen fuelled discharges gave $\alpha \sim 2 \times 10^{-5}$. These values are comparable to one another, and smaller than the critical value of $\alpha = 10^{-4}$ required for a DT molecule to be transferred to another surface before it is pumped out of the torus. Thus it seems improbable that molecular exchange processes are the cause of the tritium dispersion. It should be noted that isotopic equilibrium did appear to be reached by molecular exchange processes during the torus soaking in D_2. However, the torus is isolated from the pumps during this procedure for a time greater than 100 vacuum time constants so $\alpha \sim 10^{-5}$ is more than sufficient to reach equilibrium.

Next, we consider the effect of charge exchange neutral fluxes. The tritium injected into the plasma will diffuse towards the boundary. Plasma ions, both deuterium and tritium, are neutralised at the target. On re-entering the plasma they may either be reionised or charge exchange with a hot ion allowing a fast neutral to go to the wall. Thus the neutral trajectories provide a mechanism for tritium distribution to other torus surfaces. The NIMBUS Monte Carlo code [30] has been used to obtain a quantitative estimate of the flux to the walls. Using density and temperature profiles measured in the ohmic X-point phase after the tritium injection, the spatial distribution of the charge exchange flux was calculated. An albedo of unity was used at all surfaces. It was found that the distribution was very non-uniform, as expected, varying from a minimum of 1×10^{16} atoms-m^{-2}-s^{-1} at the bottom of the vessel to 1×10^{21} atoms-m^{-2} s^{-1} near the target plates. The integrated neutral flux to the walls was 6% of the ion flux to the target plate. The average energy of neutrals striking the vessel walls was calculated to be 100 eV.

When a surface becomes saturated under ion bombardment further implantation simply results in the displacement of an equal number of atoms out of the material [31]. Isotopic exchange experiments with ion beams have led to the

development of an isotopic mixing model which states that the rate of release of a given species is proportional to the fraction of that species in the surface. The surface will reach isotopic equilibrium with the bombarding plasma in approximately a filling time. The saturation fluence of carbon for 100 eV deuterium ions is ~$3x10^{20}$ atoms-m^{-2} [32] and the initial equilibration depth is ~8 nm. Using the fluxes calculated with the NIMBUS code and multiplying by the duration of the ohmic X-point phase of the first PTE discharge, it is found that ~75 m^2 (38%) of the vessel wall reaches equilibrium with the plasma by the end of the pulse. This area includes the upper belt limiter (Fig. 1) and explains the observation of significant tritium contamination in the limiter phase of the second PTE discharge. Since the charge exchange flux profile is completely different for limiter plasmas, further spreading of the tritium will occur. The charge exchange process provides a mechanism for rapidly distributing the tritium uniformly over the wall and we conclude that the whole wall must take part in the isotopic changeover.

At first sight this appears to be in conflict with the original hypothesis that the tritium would be found in the region of net deposition at the X-point. However recent analysis of deposition at the JET X-point is illuminating. Although erosion is limited to small areas of the target tiles at the strike points (~0.3 m^2 in total), most redeposition occurs over an area of 6.5 m^2 inboard of the outer strike zone [14]. For the two second tritium injection phase of each PTE shot, approximately 10^{21} carbon atoms are redeposited. This only produces a layer of ~1.5 nm even if all deposition is in this region, which means any tritium trapped by this layer is within the charge exchange equilibration zone (75 m^2 by 8 nm thick).

An additional mechanism for tritium spreading is the loss of particle confinement during the current rampdown. An increase in the scrape off layer thickness which accompanies the loss of confinement has been observed using deposition probes on the edge [33]. This process, although difficult to quantify, will increase the rate with which tritium is spread over the vessel surface.

6.2. Physical interpretation of the tritium release between discharges

In earlier isotopic exchange experiments the concentration of the original isotope appeared to fall off with two decay constants, a fast one with a characteristic time of a few discharges and a longer one which takes tens of discharges. This behaviour was modelled in terms of two wall reservoirs which are responsible for the decay constants [6]. A similar approach was adopted in the preparation of the PTE experiment. The constants identified in a hydrogen-to-deuterium changeover experiment were used to guide the planning of the clean-up

campaign. However when the complete data were available it was clear that the tritium release continued at a much higher level at long times than was predicted by the two reservoir model. Such an effect is difficult to identify in hydrogen/deuterium exchanges because of the significant background levels. In the case of the PTE experiment the background was about four orders of magnitude below the initial signal level and in addition the detection sensitivity was very high, thus making the deviation from the double exponential dependence very obvious, as shown in Fig. 4(c).

A probable explanation of the long term release of tritium is diffusion into the bulk, as has been suggested in some earlier studies [20-22,34]. At the end of each discharge the concentration in the implantation layer will decrease by release of gas from the surface and also by diffusion into the bulk. This process will be assisted by the growth of carbon-based plasma deposits over areas of the vessel (which in the long-term is the dominant isotope storage mechanism), and by the routine deposition of beryllium films. Over a series of discharges the concentration in the bulk will build up. When the plasma isotope is changed the bulk concentration of the original isotope will act as a reservoir diffusing back into the implanted region between discharges and then being released into the plasma.

The behaviour of the release between discharges has also to be explained. Experimentally the release rate decays approximately as a power law, although it is clear that this power law only holds over a limited time range. To model the time dependent release, we have considered the effect of hydrogen trapping in tightly bound sites. Such models have been very successful in explaining the behaviour of hydrogen release from carbon samples implanted with monoenergetic ion beams under well defined conditions [31,35]. The majority of hydrogen atoms are considered to be in tightly bound traps while the remaining atoms are in solution with a much lower binding energy. The basic trapping model assumes that all the gas exists within the implanted layer. Thus in an isotopic exchange experiment, where one isotope is being depleted by another, the concentration of the first would be expected to decrease exponentially with shot number. To explain the experimental shot-to-shot behaviour over the longer term we include diffusion. Following the suggestion of Möller [31], we allow only the population in solution to diffuse. The rate equations for the atoms of isotope i in solution, c_{Si}, and in traps, c_{Ti}, are:

$$\frac{\partial c_{Si}}{\partial t} = -K_r c_{Si} c_S H(x_0 - x) + D\frac{\partial^2 c_{Si}}{\partial x^2} - \frac{\partial c_{Ti}}{\partial t} \qquad (6.2.1)$$

$$\frac{\partial c_{Ti}}{\partial t} = -K_T \beta c_{Ti} + K_T c_{Si}(1 - c_T / c_0) \qquad (6.2.2)$$

where K_r is the recombination coefficient, c_0 is the concentration of traps, D is the diffusion coefficient, K_T is the trapping rate coefficient, β is the Boltzmann factor associated with the trap depth, and $c_T = c_{Ti} + c_{Tj}$ is the total concentration of atoms in traps.

The density of traps is assumed to be the same in the bulk material as in the implantation region. Release of gas from the sample results from recombination of the atoms in solution. The Heaviside function, $H(x_0 - x)$, is introduced to specify that recombination can occur only within the implantation region $(x < x_0)$.

To simplify the above set of equations the population in solution is assumed to be in quasi-equilibrium with the population in traps as was done by Brice [35]. The quasi-equilibrium assumption implies that release is controlled by recombination rather than detrapping. If the concentration of atoms in solution is taken to be much smaller than the concentration in traps, the equation governing the total concentration of isotope i, $c_i = c_{Si} + c_{Ti}$, is given by:

$$\frac{\partial c_i(x)}{\partial t} = -\frac{K_r \beta^2 c_i(x) c(x)}{(1 - c(x)/c_0)^2} H(x_0 - x) + D\beta \frac{\partial^2}{\partial x^2}\left(\frac{c_i(x)}{1 - c(x)/c_0}\right) \qquad (6.2.3)$$

A more complete description of the model will be published elsewhere.

Equation (6.2.3) has been solved numerically using fitted values of the constants. The actual experimental time between discharges is included in the calculation and each discharge is simulated by filling the traps within the implanted layer to saturation. The model is compared with experimental results for the shot-to-shot behaviour of the integrated gas release in the first 600 s after the shot, as shown in Fig. 4 and Fig. 6. It is seen that the amount of tritium released does not fall off exponentially with shot number since the implantation layer is now replenished by diffusion from the bulk between discharges. To simulate the helium discharges, the implantation layer was filled with an amount equal to the experimental deuterium input. This results in a concentration significantly below the saturation level, and hence a reduced tritium recovery. Qualitatively, this is in agreement with the data although the calculation overpredicts this effect (Fig. 4a).

In Fig. 7, the model calculation for the time evolution of the integrated tritium release between discharges is compared with the data for the weekend of the PTE. Just before the second PTE discharge, 20% of the tritium injected in the first one has been released. The release rate is enhanced after the second PTE so that

immediately before the first clean-up shot (1.64×10^5 s) about 40% of the tritium injected in both PTE discharges has been recovered. In Fig. 8, the calculated release rates for both deuterium and tritium are shown for two discharges. The experimentally measured deuterium release rates are shown for comparision. The curves are consistent with a power law behaviour (Eq. 5.2.1), with an exponent of ~0.7.

The calculated tritium depth distribution, obtained from the model including diffusion, is shown in Fig. 9. Immediately after the PTE discharge the tritium is completely within the implantation layer. In subsequent discharges the near-surface concentration decreases and the concentration in the bulk increases. At very long times the dominant effect is the diffusion from the bulk towards the surface, between discharges. The release of tritium at long times is however dependent on whether or not there are discharges. The saturation of the implantation layer due to discharges provides a mechanism for the release of tritium which has diffused back into this region. The recombination rate is enhanced by the increased deuterium concentration near the surface and the implantation layer becomes a sink for diffusing tritium when it is periodically refilled with deuterium.

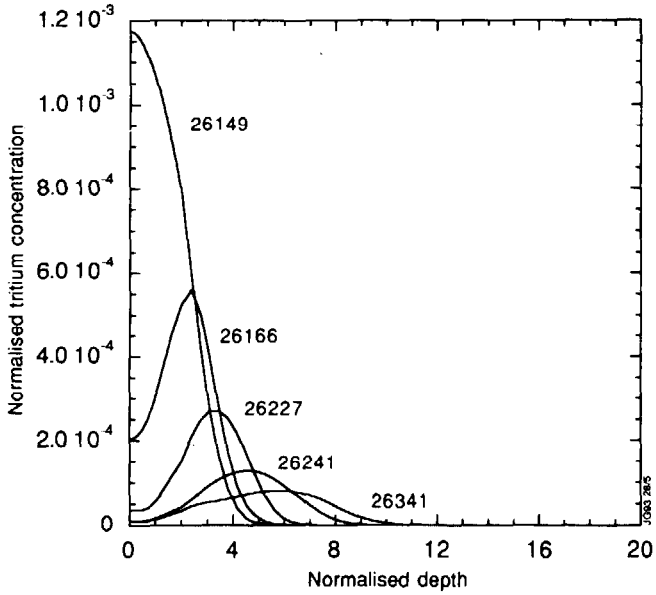

Fig. 9: Calculated depth profiles of tritium at various stages after the tritium injection (26147 and 26148 were the two PTE discharges). The tritium levels are normalised to the saturation concentration of hydrogen in carbon. The depth is normalised to one implantation layer (8 nm).

In the model calculations, no provision was made to model the effects of additional heating or disruptions. Possibly in these discharges higher particle energies result in a thicker implantation layer or in enhanced recombination and diffusion due to heating of surfaces. These effects would increase the amount of tritium released, as was observed experimentally.

The model calculation gives tritium inventories in the first wall of 1.1×10^{20} atoms 2 weeks after the PTE shots, and 3.8×10^{19} atoms at the end of the experimental campaign. These are in agreement with the measured inventories given in Table 1.

In fitting the model calculations to the data three quantities were adjusted:

1) the total number of traps in the implantation layer;
2) the recombination rate;
3) the diffusion rate.

It is clear that the recycling behaviour of JET changed dramatically when beryllium was introduced [36]. As such, the parameters in our model do not represent those of a pure carbon machine. It is instructive, nonetheless, to compare our results with data from ion beam experiments on graphite [31,35].

The number of traps in the implantation layer is given by Ax_0c_0, where A is the total surface area. A good match to the data was obtained with 1.65×10^{23} traps. The number of traps over the whole JET vacuum vessel projected area which can be filled by 100 eV D atoms to saturation is $200\ m^2 \times 8\ nm \times 0.4\ D/C \times 9\times10^{28}\ m^{-3} = 5.8\times10^{22}$. The discrepancy between this estimate and the fitted value is well within the uncertainty in the calculated trap population due to uncertainty in the charge exchange neutral energies. Experimental measurements of charge exchange average energies up to 400 eV have been obtained in PLT and ASDEX on discharges at similar densities [37-39].

The recombination rate in the model calculations is determined by the group of constants $K_r\beta^2c_0=1\times10^{-6}\ s^{-1}$. This can be compared with Brice's group of constants $K(N_s/N_t)^2a_b^2N_t/R$ [35]. In Brice's model the recombination takes place at the surface only, so that the particle range R enters into the parameter. Taking the values used by Brice to fit isochronal annealing of graphite for T=300°C, and R=8 nm gives a value of $K_r\beta^2c_0\sim2\times10^{-4}\ s^{-1}$. Alternatively, the group of constants used by Möller [31] to describe similar data gives $K_r\beta^2c_0\sim4\times10^{-23}\ s^{-1}$. The reason for this large discrepancy is the different activation energies used by these authors. The large difference in activation energy leads to the large spread in $K_r\beta^2c_0$ values at 573 K while not greatly affecting the fit to the anneal data. Our fitted value lies between the two extrapolated values. In the present modelling, there is no choice of activation energy since there is only one experimental temperature.

Finally, the third adjustable parameter is the effective diffusion rate $\beta D/x_0^2$. D is the diffusion coefficient for atoms in solution and βD is the diffusion coefficient which describes the movement of the whole population c (in traps and solution) when $c \ll c_0$. Assuming $x_0=8$ nm, the model calculations give $\beta D=2.6\times10^{-22}\ m^{2}\text{-}s^{-1}$. This lies within the large span of values, $\sim10^{-30}\text{-}10^{-19}\ m^{2}\text{-}s^{-1}$, obtained by extrapolating data for graphite [40] down to T=300°C.

The model allows the behaviour of the tritium to be calculated for hypothetical clean-up scenarios. We have considered the case of clean-up pulses starting immediately after the PTE discharges. The consequence is that the initial diffusion into the bulk is lower. This increases the initial release rate in successive pulses resulting in a lower inventory after about 50 discharges. Subsequently the release per discharge is reduced and the inventory remains a constant factor of ~1.6 less than the value obtained when there is an initial 40 hour interval between the PTE and the start of the clean-up campaign.

7. CONCLUSIONS

The PTE experiment offered a unique opportunity to study the isotopic exchange processes in a large tokamak and to follow the release rate over nearly four orders of magnitude in concentration. The primary objective of removing most of the tritium was successfully accomplished. The tritium inventory was reduced to 3.4×10^{19} atoms at the end of the operations, i.e. to as little as 3% of the injected tritium.

A number of different methods of removing tritium were compared. Standard ohmic discharges were reasonably effective and additional heating produced only a marginal improvement. The most effective method was disruptive discharges in deuterium which were two times better than standard discharges. After about two weeks operation the tritium level was sufficiently low that evacuation into the sealed-off backing line could be discontinued and use of the conventional backing pumps resumed.

An initially surprising result was that even though tritium was injected only during X-point conditions the tritium was found to be rapidly distributed uniformly over all the tokamak surface. This occurs as a result of charge exchange neutral fluxes to the wall which are large enough in JET to maintain an equilibrium isotopic balance over large areas of the vessel. Using the results of a Monte Carlo neutral transport code, it was shown that even in the limiter phase of the second PTE shot significant contamination of the plasma should be expected. As such, at least with geometries and neutral fluxes typical of JET, careful control of the plasma position during termination is ineffective in maintaining localised tritium contamination of the vessel wall.

The release of tritium between discharges was modelled using existing theories which have previously been used to model ion beam experiments with graphite. It was necessary, however, to include an additional mechanism, diffusion, to model the long term release of tritium from the torus. This model gives good

agreement with the time dependence of the outgassing between discharges, the shot-to-shot release, and the tritium inventory long after the tritium experiment. Using the model it has been calculated that the final tritium inventory in the torus could have been reduced by a factor of 1.6 if the clean-up campaign had been started immediately after the PTE rather than waiting for 40 hours.

Soaking of the torus at pressures of ~2 Pa of deuterium was found to be an effective, operationally simple way of removing tritium from the machine. Although the equilibration time between the gas load and the vessel walls was not measured, it is estimated from other experiments to be approximately 5 minutes. If this molecular exchange process can be shown to access the entire implantation layer of the vessel wall, it may be possible to remove tritium more quickly, and thus with lower diffusion losses to the bulk wall material, using gas purges rather than plasma discharges.

The data obtained has enabled us to get a much better understanding of the principle processes occurring. This should enable the behaviour of tritium in the next tritium phase of JET to be predicted with some confidence. However, because the rates of physical processes are dependent on material properties the absolute values of the model parameters will change if the vessel materials are changed. An isotope exchange experiment with hydrogen and deuterium is therefore necessary to validate the model parameters for different machine conditions.

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REFERENCES

[1] JET Team, Nucl. Fusion **32** (1992) 187.

[2] Ehrenberg, J., Philipps, V., de Kock, L., Causey, R.A., Hsu, W.L., J. Nucl. Mater. **176&177** (1990) 226.

[3] Hemmerich, J.L., Lässer, R., Winkel, T., Fusion Engrg. Des. **19** (1992) 161.

[4] Falter, H.D., Thompson, E., Ciric, D., de Esch, H.P.L., J. Nucl. Mater. **196-198** (1992) 1131.

[5] Saibene, G., Sartori, R., Andrew, P., et al., Fusion Engrg. Des. **19** (1992) 133.

[6] Horton, L.D., Andrew, P., Bracco, G., et al., J. Nucl. Mater. **196-198** (1992) 139.

[7] Hemmerich, J.L., Dombra, A., Gowman, J., et al., Fusion Engrg. Des. **11** (1989) 93.

[8] JET Team, in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 13th Int. Conf. Washington, D.C., 1990), Vol. 1, IAEA, Vienna (1991) 261.

[9] Reichle, R., Nucl. Fusion (companion paper).

[10] Hsu, W.L., Causey, R.A., J. Vac. Sci. Technol. A **5** (1987) 2768.

[11] Bergsåker, H., Coad, J.P., Behrisch, R., et al., J. Nucl. Mater. **176&177** (1990) 941.

[12] Reichle, R., Clement, S., Gottardi, N., et al., in Controlled Fusion and Plasma Physics (Proc. 18th Eur. Conf. Berlin, 1991), Vol. 15C, Part III, European Physical Society (1991) 105.

[13] Coad, J.P., Behrisch, R., Bergsåker, H., et al., J. Nucl. Mater. **162-164** (1989) 533.

[14] Coad, J.P., Farmery, B., Linke, J., Wallura, E., Experience with boron-carbide coated target tiles in JET, to be published in J. Nucl. Mater.

[15] Balet, B., Stubberfield, P.M., Cordey, J.G., et al., Nucl. Fusion (companion paper).

[16] Caldwell-Nichols, C.J., Hemmerich, J.L., Lässer, R., Milverton, P., The design and performance of the JET ionisation chambers for use with tritium, to be published in Proc. 17th Symp. on Fusion Technol. (SOFT-17).

[17] Sartori, R., Saibene, G., Goodall, D.H.J., et al., J. Nucl. Mater. **176&177** (1990) 624.

[18] Goodall, D.H.J., Andrew, P., Ehrenberg, J., et al., J. Nucl. Mater. **196-198** (1992) 1002.

[19] Sadler, G., Jarvis, O.N., van Belle, P., Pillon, M., Rev. Sci. Instrum. **61** (1990) 3175.

[20] McCracken, G.M., Fielding, S.J., Erents, S.K., Pospieszczyk, A., Stott, P.E., Nucl. Fusion **18** (1978) 35.
[21] TFR Group, Terreault, B., J. Nucl. Mater. **127** (1985) 18.
[22] LaMarche, P.H., Dylla, H.F., McCarthy, P.J., Ulrickson, M., J. Vac. Sci. Technol. A **4** (1986) 1198.
[23] Andrew, P., Caldwell-Nichols, C.J., Coad, J.P., et al., J. Nucl. Mater. **196-198** (1992) 143.
[24] Coad, J.P., Gibson, A., Haigh, A.D., Kaveney, G., Orchard, J., in Controlled Fusion and Plasma Physics (Proc. 18th Eur. Conf. Berlin, 1991), Vol. 15C, Part III, European Physical Society (1991) 81.
[25] Peacock, A.T., Coad, J.P., Dietz, K.J., Knight, A.P., Tritium retention in first wall material at JET after the first tritium experiment (FTE), to be published in Proc. 17th Symp. on Fusion Technol. (SOFT-17).
[26] Philipps, V., Ehrenberg, J., Analysis of outgassing after JET discharges under beryllium first wall conditions, to be published in J. Vac. Sci. Technol.
[27] Hoinkis, E., J. Nucl. Mater. **182** (1991) 93.
[28] Lossev, V., Küppers, J., J. Nucl. Mater. **196-198** (1992) 953.
[29] Hayward, D.O., Trapnell, B.M.W., Chemisorption, Buttersworth, London (1964).
[30] Cupini, E., de Matteis, A., Simonini, R., NIMBUS - Monte Carlo simulation of neutral particle transport in fusion devices, Rep. EUR XIII, 324/9, ENEA, Bologna (1983).
[31] Möller, W., J. Nucl. Mater. **162-164** (1989) 138.
[32] Staudenmaier, G., Roth, J., Behrisch, R., et al., J. Nucl. Mater. **84** (1979) 149.
[33] Bergsåker, H., Coad, J.P., de Kock, L., et al., in Controlled Fusion and Plasma Physics (Proc. 14th Eur. Conf. Madrid, 1987), Vol. 11D, Part II, European Physical Society (1987) 732.
[34] Ehrenberg, J., J. Nucl. Mater. **145-147** (1987) 551.
[35] Brice, D.K., Nucl. Instrum. Methods **B44** (1990) 302.
[36] JET Team, J. Nucl. Mater. **176&177** (1990) 3.
[37] Ruzic, D.N., Heifetz, D.B., Cohen, S.A., J. Nucl. Mater. **145-147** (1987) 527.
[38] Verbeek, H., Dose, V., Fu, J.K., et al., J. Nucl. Mater. **162-164** (1989) 557.
[39] Verbeek, H., Poschenrieder, W., Carlson, A., et al., Plasma Phys. Control. Fusion **32** (1990) 651.
[40] Wilson, K.L., Bastasz, R., Causey, R.A., et al., Supplement to Nuclear Fusion **1** (1991) 31.